



Golder Associates Ltd.

CONSULTING ENGINEERS

REPORT TO
CANMET
ON

IN SITU STRESS MEASUREMENTS
AT LINGAN COLLIERY
CAPE BRETON, NOVA SCOTIA

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ABSTRACT

A programme of in situ stress measurements in Lingan Colliery of the Sydney coalfield in Cape Breton was completed during February 1991, as part of a joint cooperative research programme between the Cape Breton Development Corporation (CBDC) and the CANMET, Cape Breton Coal Research Laboratory. The measurements were undertaken in three 96 mm diameter drillholes located at the north end of the No. 4 deep, approximately 340 m down slope of 13 East bottom/14 East top drivages. The in situ stresses were measured by the method of overcoring using the U.S. Bureau of Mines (USBM) deformation gauge.

A total of nine overcoring tests were attempted of which eight were successful. The test data was used to evaluate:

- the secondary principal stresses (for individual tests) on a plane perpendicular to the drillhole axis for the case of plane strain; and
- the average stress tensor in the siltstone strata by applying the method of least squares.

The results of the least squares solution indicate that there is reasonably good correlation between independent measurements carried out in three separate drillholes. The principal stresses calculated from the least squares solution are as follows:

<u>Principal Stresses</u>	<u>Azimuth</u>	<u>Dip*</u>
σ_1 = 38.45 MPa	297°	9°
σ_2 = 20.55 MPa	31°	24°
σ_3 = 15.55 MPa	9°	-65°

* Positive dip inclined upward from horizontal.

The stresses determined in the current (1991) series of measurements in Lingan Colliery are anisotropic and about 15% higher than the 1986 results. The orientations of the intermediate and minor principal stresses are slightly different from previous measurements. The overall results are consistent with the greater depth and steepening of the rock strata at the current test site.

The anisotropic stress state at Lingan Colliery is considered to have been influenced by the New Waterford Monocline which is located in the vicinity of the stress measurement locations. At comparable depth, the in situ stress state at No. 26 Colliery, which is not influenced by any major geological structure, is approximately isotropic.

RÉSUMÉ

Un programme de mesure des contraintes in-situ fut réalisé à la Houillère Lingan, près de Sydney, Cap-Breton en février 1991, pour la part d'un programme de recherche coopératif entre la Société de Développement du Cap-Breton et les Laboratoires de Recherche sur le Charbon du Centre Canadien de la Technologie des Minéraux et de l'Énergie. Les mesures furent entreprises dans trois forages de 96 mm diamètre localisés au bout du nord du pendage No. 4, approximativement 340 m descendant du tunnel de 13 Est bas/14 Est haut. Les contraintes in-situ furent mesurées par la méthode de surforage en utilisant les cellules du USBM.

Un total de neuf surforage furent essayés dans lesquels huit essais furent couronnés de succès. Les résultats des essais furent utilisés à évaluer:

- les contraintes principales secondaires (pour les essais individuels) sur un plan perpendiculaire à l'axe du forage pour le cas de déformation plane; et
- le tenseur de contrainte moyenne dans la couche de siltstone par la méthode de moindre carrés.

Les résultats de la solution de moindre carrés indiquent qu'il y a de bonne corrélation entre les mesures réalisés dans les trois forages séparés. Les contraintes principales déterminées par la méthode de moindre carrés sont comme suivantes:

<u>Contraintes Principales</u>	<u>Azimuth</u>	<u>Pendage*</u>
σ_1 = 38.45 MPa	297°	9°
σ_2 = 20.55 MPa	31°	24°
σ_3 = 15.55 MPa	9°	-65°

* positif pour un pendage vers le haut de horizontal

Les contraintes déterminées dans les mesures courants (1991) à la Houillère Lingan sont trouvés en 1986. Les orientations des contraintes principales intermédiaires mineurs sont un peu différentes que les mesures précédents. Les résultats généraux sont consistents avec ceux-là trouvés dans les couches de roche plus profondes et plus inclinées, dans le chantier d'essai courant.

L'état de contrainte anisotropique à la Houillère Lingan est considéré avoir été influencé par une structure monoclinale de New Waterford qui est située au voisin des locations de mesure des contraintes. Dans une profondeur comparable, l'état de contrainte in-situ à la Houillère No. 26, qui n'est pas influencé par la structure géologique majeure, est approximativement isotropique.

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1 INTRODUCTION

Lingan Colliery is one of the producing mines of the Sydney coalfield owned and operated by the Cape Breton Development Corporation (CBDC) in Cape Breton, Nova Scotia. A test programme to obtain in situ stress data in the deepest part of the mine was proposed by CANMET, Cape Breton Coal Research Laboratory (CBCRL).

Golder Associates was awarded a contract under the auspices of CANMET through Supply and Services Canada (DSS Contract No. 15SQ.23440-0-9246) to undertake this measurement programme. The objectives of the programme were as follows:

- undertake a series of overcoring in situ stress measurements using the U.S. Bureau of Mines (USBM) deformation gauge;
- undertake a series of overcoring in situ stress measurements using the Auckland New Zealand Soft Inclusion (ANZSI) cell, if time permits; and
- compare and evaluate the results with those already undertaken elsewhere in the Sydney coalfield.

Due to time and schedule constraints it was not possible to carry out the ANZSI cell tests in this stress measurement programme. Hence the results reported herein pertain only to overcoring tests with the USBM gauge.

2 TEST LOCATION AND GEOLOGICAL CONDITIONS

Lingan Colliery is a sub-sea coal mine located about 4.6 km offshore from New Waterford (see Figure 1). The mining development area extends approximately 4.3 km in the E-W and 4.6 km in the N-S direction (with reference to the mine co-ordinate system) and is currently proceeding in a northerly direction (approximately N 4° E) following the Harbour coal seam which has an average dip (downward) from 5° to 14° in the deeper sections. Longwall mining techniques are being used for the coal extraction.

The site for in situ stress measurements was located at the north end of the No. 4 deep, approximately 600 m from the boundary of the current mining development area (start of the 12 east wall) and approximately 820 m below sea level. Overcoring tests were carried out in three (3) 96 mm diameter (HQ size) holes drilled from a 5.5 m wide section of the No. 4 deep at orientations and inclinations shown in Figure 2. In general, tests in each drillhole were commenced about 13 m from the collar of the hole so that the test positions would be outside the zone of stress influence of the tunnel development. Due to the dip of the tunnel at the test site it was only possible to drill at shallow angles to the horizontal. The depth of the drillholes and the test positions are summarized in Table 1.

At the test site, the coal seam is approximately 1.5 m thick, above the floor of the development tunnel. The seam is overlain by a siltstone/sandstone strata comprising fresh, medium to thickly bedded, laminated, medium grey, very fine grained siltstone, interbedded with fresh, thinly to thickly bedded, laminated, light grey, fine to medium grained sandstone and occasional black carbonaceous partings.

3 PROCEDURE FOR STRESS MEASUREMENT

In this test programme, the in situ stresses were measured by the method of overcoring developed by the United States Bureau of Mines (USBM) (Hooker and Bickel¹ 1974). The statement of work also called for the use of the Auckland New Zealand Soft Inclusion (ANZSI) cell to be used if time permitted. As significant time was spent in the setting up at the beginning of the project, and CBDC required the drill rig back as soon as was possible, these tests were not carried out. All field work was carried out during February 1991.

The USBM overcoring measurements require that three holes be drilled to determine the complete stress tensor. The holes were drilled as showing in Figure 2 and in the orientations given in Table 1. Each of the holes were drilled in different orientations so that the three dimensional state of stress could be determined using the least squares technique (Panek² 1966).

The drilling was undertaken by Logan Geotech Inc. under a subcontract from Golder Associates Ltd.

3.1 General Test Procedure

The general procedure of the overcoring method is illustrated in Figure 3. A 96 mm diameter (HQ size) hole was drilled to about 250 mm short of the required location for the stress measurement test. A 38 mm diameter (EX size) pilot hole (approximately 600 mm in length) concentric with the 96 mm diameter hole was drilled through the test position. The USBM deformation gauge (see Figure 4) was then installed in the pilot hole in an area free of joints or fractures, normally at 200-300 mm from the end of the 96 mm diameter hole. The pilot hole was then overcored using a 96 mm thin wall coring bit to relieve the stresses around the pilot hole. The corresponding changes in diametral deformation of the pilot hole were monitored during overcoring using the USBM deformation gauge connected by cable through the drill string to a digital strain indicator, and a switch and balance unit. The stresses were evaluated from the measured changes in the deformation, and the deformation modulus determined by testing the overcored rock sample in a biaxial chamber (see Figure 4).

3.2 USBM Deformation Gauge

The USBM deformation gauge (see Figure 4) is designed to measure the changes in the deformation of the pilot hole across three diameters (spaced 120° apart). The gauge has three pairs of buttons which provide contact between the surface of the 38 mm diameter pilot hole and the sensing element of the gauge. A cable connects the gauge with the readout unit through the drill string allowing continuous observation of the borehole deformation changes during overcoring. This instrument enables the measurement of the two-dimensional stress field on a plane normal to the axis of the drillhole. Details of this instrument and the operational procedure have been described by Hooker and Bickel¹ (1974).

3.3 Biaxial Testing Equipment

The deformation modulus of the overcore sample recovered from the test position was determined using a biaxial test cell. The cell essentially consists of a cylindrical steel jacket and seals. The overcored rock sample recovered from the test position is tested in the cell with the USBM gauge inside the sample. The general arrangement of the biaxial test equipment is shown in Figure 4.

The recovered overcore sample is placed in the biaxial chamber with the USBM gauge installed in the same configuration as the overcore test. Hydraulic oil is pumped into the space between the steel jacket and the sealed membrane which is in contact with the overcore. The outer surface of the overcore is therefore subjected to a uniformly distributed radial (biaxial) pressure. During modulus testing, the deformation of the inner hole of the overcore sample is monitored at various pressure increments and decrements.

3.4 Drilling Equipment

The stress measurement drillholes were drilled using a Longyear 38 underground drill supplied by the Cape Breton Development Corporation. The general arrangement and set up of the drill rig at the test site is shown in Figure 5.

Since drilling is the most expensive component of the stress measurement programme, recent measurements have been carried out using standard HQ (96 mm diameter) boreholes rather than the originally designed 150 mm diameter holes. This equipment is more readily available and is easier and cheaper to use. Apart from the standard HQ wireline equipment

used for drilling the H size borehole, specialized ancillary drilling equipment was used to facilitate the drilling of the pilot hole and the overcoring operation. A list of the specialized drilling equipment and an outline of the procedure in using this equipment is given in Appendix C.

3.5 Certification of Testing Equipment

In compliance with statutory equipment of the Coal Mines (CBDC) Safety Regulations, all electrical equipment (including their circuitries) and installation tools used for stress measurements have been certified by the Mining Research Laboratories of CANMET. This set of equipment was also approved by Labour Canada (Sydney).

4 RESULTS OF TESTS

4.1 General

A total of nine (9) overcoring tests were attempted during this series of stress measurement, three (3) in hole 1, one (1) in hole 2, three (3) in hole 3 and two (2) in hole 4. All tests were successful with the exception of the one carried out in hole 2. This hole, which was drilled down beneath the coal seam, squeezed such that the tests could not be carried out. One other test U3-1 gave results that were inconsistent with the rest of the tests. Although the values have been reported they have not been used in the least squares analysis.

The test positions in each drillhole and the problems, if any, encountered during testing are summarized in Table 1. Results of the overcoring and biaxial tests are presented in the following sections.

4.2 Results of Overcoring Tests

During the overcoring tests, the diametral deformation of the pilot hole was monitored continuously. The measured diametral deformations, as calculated from the recorded strain readings, for the three button positions (designated as U_1 , U_2 , and U_3 respectively) are plotted against the depth of overcoring measured from the collar of the pilot hole. The results of the tests are shown in graphical form in Figures A.1 to A.8. No data was available from test U2-1 since it was aborted due to problems described in Table 1.

The results of tests generally showed the classic response that could be expected from good overcoring tests. Typically, the readings were stable during the initial stages and showed distinct changes when the overcore bit approached and subsequently passed the button positions. The readings again became stable as overcoring continued beyond the button positions. Based on the plots shown on Figure A.1 to A.8, the total diametral deformations of the pilot holes for each of the successful overcoring tests are summarized in Table 3.

It should be noted that test results were very consistent within each of the boreholes, giving a very good data set.

4.3 Results of Biaxial Tests

Biaxial tests were carried out on the overcore samples retrieved from the tests to determine the deformation modulus. Figures B.1 to B.5 in Appendix B show the results of these tests. In general, the curves of deformation against pressure show a fairly linear response with a little hysteresis during unloading. The biaxial test carried out on the sandstone sample (Test U3-3) shows hysteresis in the trend, however the least squares analysis has only included siltstone samples. Table 2 summarizes the average modulus values calculated from the biaxial tests undertaken.

It was not possible to test the recovered samples from overcore tests U1-2, U3-1 and U3-2 as the recovered intact samples were too short to fit in the biaxial chamber; modulus values for these tests were assumed from adjacent tests.

A Poisson's ratio of 0.2 was assumed throughout; the calculation of in situ stress magnitudes is not sensitive to this parameter.

4.4 Evaluation of Elastic Constants and In situ Stresses

4.4.1 Evaluation of Elastic Constants

The deformation modulus of the rock was evaluated based on the results of the biaxial tests using the following expression and assuming isotropic elasticity.

$$E = \frac{4ab^2P_o}{(b^2 - a^2)U}$$

where	E	= Deformation modulus,
	a	= the inner radius of the overcore,
	b	= the outer radius of the overcore,
	P _o	= pressure on the outer surface of the overcore,
and	U	= Diametral deformation of pilot hole in the overcore

Where the deformations across the three diameters varied, the average diametral deformation was used for the evaluation of the average deformation modulus.

A comparison of the isotropic and anisotropic interpretation of the state of in situ stresses has been given by Becker and Hooker³ (1976). The order of error that may be made in determining the stresses in anisotropic rock by using isotropic expression was also examined.

Based on the results of their study, it is noted that for an approximately isotropic stress field, the errors involved in determining the state of stress by using isotropic expressions are insignificant for the degree of anisotropy observed in the present tests. Hence, it is acceptable to use the average deformation modulus from the biaxial test for the evaluation of in situ stresses for the present study.

The average deformation modulus of the samples recovered from the overcoring tests are summarized in Table 2.

Poisson's ratio of the rock was not measured directly from the biaxial test using the USBM gauge. A value of 0.2 was assumed for the Poisson's ratio for the purpose of stress evaluation.

4.4.2 Evaluation of In situ Stresses

The interpretation of the overcoring test data is based on the assumption that the rock is homogeneous and linearly elastic. Two interpretation procedures are considered in this report:

- a. evaluation of the secondary principal stresses on a plane perpendicular to the axis of the borehole assuming that the stress changes during overcoring occur under plane strain conditions; and
- b. evaluation of the complete three-dimensional stress system by pooling all the data and using a least squares solution for the complete stress tensor (Panek² 1966). The orientations of the drillholes and diametral deformation measurements are taken into account in this interpretation.

Outlines of the above data reduction procedures are described in Appendix D. In both cases, the diametral deformations, the rock deformation moduli and Poisson's ratios were used for the analysis. The secondary principal stresses calculated by the procedure described in (a) and in Appendix D, Section D.1 are summarized in Table 3.

The input parameters and the results of the in situ stresses evaluated by the procedure described in (b) are presented in Table 4. Detailed procedures for the evaluation of the

stress components are given in Appendix D, Section D.2. The results as shown in Table 5 include:

- the six independent stress components σ_x , σ_y , σ_z , τ_{xy} , τ_{yz} and τ_{zx} with respect to the mine co-ordinate system (x, y and z correspond to E-W, N-S and the vertical directions respectively);
- the standard deviations of the stress components and the correlation coefficient of the multilinear regression analysis in the least squares solution; and
- the magnitudes and directions of the principal stresses based on the average values of the six stress components.

Detailed procedures for the evaluation of the stress components are given in Appendix D, Section D.2.

5 DISCUSSION OF TEST RESULTS

5.1 State of In situ Stress

The determination of the secondary principal stresses perpendicular to the drillhole axis was based on isotropic theory and average elastic modulus values shown in Table 2. The effect of variations in the elastic moduli on the in situ stress calculation was examined based on the considerations discussed by Becker and Hooker³ (1976). The maximum ratio of maximum to minimum modulus obtained from biaxial tests is about 1.35. For this anisotropy ratio, the error involved in the calculation of the in situ stresses using the isotropic theory is less than 5%. The magnitudes of the in situ stresses (Table 3) within the siltstone unit are consistent. Only one test was carried out in the sandstone unit, the results are also consistent with those from the siltstone unit.

Drillhole orientations and test positions within each hole were selected to optimize the information from the tests and give the best statistical interpretation. Stress analyses were carried out to evaluate the stress distribution around the tunnel from which the stress measurements were undertaken. The results indicated that at a depth of 2 x tunnel diameter (5.5 m) the in situ stresses would be within 5% of the virgin state of stress. Hence the tests were located at a distance of greater than 12.5 m from the tunnel (see Table 1).

The determination of the complete stress tensor for the tests carried out in Lingan Colliery was based on the least squares solution that takes into consideration the effects of axial stress along the drillhole. The average modulus values shown in Table 4 were used in the analysis. The effects of variations in the elastic modulus values on the in situ stresses was also examined by using individual modulus values shown in Table 2, for each of the corresponding button positions. The resulting principal stresses are within 6% of those calculated based on average modulus.

The results presented in Table 5 indicate that there is a reasonable correlation between the independent measurements although the standard deviation of σ_x is higher than would have been generally expected. Transforming the stress tensor into horizontal and vertical components (Table 5) produces the following:

$$\begin{aligned}\sigma_{\text{east-west}} &= 33.19 \text{ MPa} \\ \sigma_{\text{north-south}} &= 21.21 \text{ MPa} \\ \sigma_{\text{vertical}} &= 20.15 \text{ MPa}\end{aligned}$$

A comparison of the measured vertical stress (σ_z) and the static vertical stress (σ_v) was made to verify the above results as follows:

- (i) Average vertical stress (σ_z) = 20.15 MPa
calculated from least squares (SD = 3.85 MPa)
solution (Table 4)

- (ii) Static vertical stress (σ_v)
calculated on the basis
of the following parameters:
- Depth of test site below seabed = 730 m
 - Depth of sea at test site = 90 m
 - Density of rock = 2.72 Mg/m³
 - Density of seawater = 1.025 Mg/m³

Hence vertical static stress (σ_v) = 20.78 MPa

The principal stresses calculated from the least squares solution are as follows:

<u>Principal Stresses</u>	<u>Azimuth</u>	<u>Dip</u>
σ_1 = 38.45 MPa	297°	9°
σ_2 = 20.55 MPa	31°	24°
σ_3 = 15.55 MPa	9°	-65°

The major principal stress of 38.45 MPa acts in a near east - west direction at an inclination of 9°. Since the test site is located approximately 600 m from existing mine development (12 East Wall) it is considered that the in situ stresses measured in this programme reflect the virgin in situ stresses existing at this location.

5.2 Orientation of In situ Stresses

The orientations of the secondary principal stresses as calculated using equation D3 in Appendix D are given in Table 3. In general the stress orientations measured within each drillhole are consistent. It can be seen from drillhole LC4S-1 that the three test results give an orientation of P from the U_1 button of between 51.5° and 57.5°; with tests U1-2 and U1-3 being almost identical. The spread of results from these tests is considered to be exceptionally good. Similarly the spreads shown between tests U3-2 and U3-3 in drillhole LC4S-3, and U4-1 and U4-2 in drillhole LC4S-4 are within a range of $\pm 15^\circ$. Test U3-1 was not used in the interpretation.

6 COMPARISON OF STRESSES IN THE SYDNEY COALFIELD

In situ stress measurement programmes have been undertaken in a number of coal mines in the Sydney Coalfield in the past eight years. Each of these programmes have been carried out by Golder Associates Ltd.⁽⁵⁻⁸⁾ under contracts from Supply and Services, Canada. A summary of the results is given in Table 6.

The test site for the current series of measurements is in the deepest part of Langan Colliery, and at a depth comparable to that where tests were carried out in No. 26 Colliery. The vertical stress component calculated from the least squares solution compares very well with the calculated vertical static stress and is consistent with findings at other sites within the Sydney Coalfield.

6.1 Langan Colliery Measurements

The results from the current (1991) and previous (1986) series of tests at Langan Colliery are generally consistent. The test site for the current measurements is considerably deeper and is located in an area where the dip of the strata is approximately 14° compared with an 8° dip at the 1986 test site.

The principal stresses, as shown in Table 7, are about 15% higher than the 1986 values. The major principal stress component is generally in the E-W direction, consistent with previous measurements. The intermediate and minor stress directions are slightly different, due probably to the steepening of the strata at the deeper test location.

A comparison of the E-W, N-S and vertical components from the two series of measurements indicate that there is an increase in the vertical stress component as expected. The E-W component remains virtually unchanged whereas there is a substantial increase in the N-S stress component. It appears that the overall stress anisotropy has decreased at the deeper part of the mine. However the maximum to minimum horizontal stress ratio only drops very slightly.

6.2 Comparison of Langan Colliery and No. 26 Colliery Measurements

A comparison of the principal stresses and horizontal stress components determined in both Langan Colliery and No. 26 Colliery is given in Table 7. The horizontal stresses at the test sites are presented graphically in Figure 6.

Within Langan Colliery, the principal stresses are generally anisotropic compared with the isotropic state of stress in No. 26 Colliery. A similar trend is evident in the horizontal stress components as shown by the maximum and minimum horizontal stress ratios of 2.32 and 2.45 for Langan Colliery, and 1.07 for No. 26 Colliery (see Table 7).

The anisotropic stress state at Langan Colliery is considered to have been influenced by the New Waterford Monocline in the vicinity of the stress measurement locations. On the other hand, No. 26 Colliery is not influenced by any major geological structure.

7 CONCLUSIONS

The in situ stress measurement programme for Lingan Colliery of the Sydney Coalfield in Cape Breton was completed in February 1991. A total of nine USBM overcoring tests were undertaken in three 96 mm diameter, near horizontal and inclined drillholes located in the siltstone and sandstone strata overlying the coal seam at the northern end on No. 4 slope. The conclusions derived from these tests are summarized below.

- Of the nine USBM tests undertaken, eight of the tests were successful. The one test that was unsuccessful was attempted in a sub-horizontal hole drilled below the coal seam. This hole caved and no measurements were possible.
- Based on the results of the biaxial tests, the rock tested showed some anisotropy in modulus for some tests. The effect of this anisotropy was investigated and the resulting stresses were within 5% of the analysis based on average modulus values.
- There was a significant difference in modulus between the siltstone and sandstone. Despite the difference the secondary principal stresses measured in the two strata are reasonably consistent.
- The results of the least squares solution for the stress tensor indicate that there is reasonable correlation between independent measurements carried out in the three separate drillholes. The standard deviation of the σ_x value is however higher than would have been anticipated.
- The stresses determined in the current (1991) series of measurements in Lingan Colliery are anisotropic and about 15% higher than the 1986 results.
- The orientation of the major principal stress is consistent with the previous measurements and the intermediate and minor stress directions are slightly different. A comparison of the E-W, N-S and vertical components from the two series of measurements indicate that there is an increase in the vertical stress component as expected. The E-W component remains virtually unchanged whereas there is a substantial increase in the N-S stress component. It appears that the overall stress anisotropy has decreased at the deeper part of the mine. However the maximum to minimum horizontal stress ratio only drops very slightly.
- In comparing stresses in Lingan Colliery with those of No. 26 Colliery, it is considered that the influence of the New Waterford Monocline is the cause

for the anisotropy in stress. No. 26 Colliery is not influenced by any major geological structure.

8 ACKNOWLEDGEMENTS

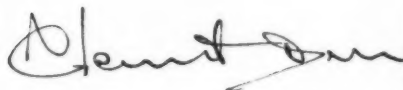
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Table 1 Summary of Positions of Overcoring Tests

Drill Hole	Rock Type	Drill Hole Orientation		Test No.	Depth of Test from Hole Collar (m)	Comments on Tests
		Azimuth (°)	Dip (°)			
LC4S-1	Siltstone	124	30	U1-1	12.92	a, d
	Siltstone			U1-2	13.55	a, e
	Siltstone			U1-3	13.98	a, d
LC4S-2	Sandstone	124	-10	U2-1	12.65	b, c, f
LC4S-3	Siltstone	79	20	U3-1	12.50	a, e
	Siltstone			U3-2	12.78	a, e
	Sandstone			U3-3	13.13	a, d
LC4S-4	Siltstone	79	4	U4-1	13.13	a, d
	Siltstone			U4-2	13.59	a, d

1. Comments on Tests:

- a. Successful overcore test.
- b. "Caved" material above test position may have been trapped in the overcore bit when installed; this material interfered with the USBM gauge; no results obtained.
- c. Hole caved subsequent to attempted test; hole abandoned.
- d. Core recovered from test for biaxial test.
- e. Retrieved core not long enough to carry out biaxial test.
- f. Unsuccessful test.

2. Notes:

- i. Holes were not surveyed. Hole directions and dip have been determined using a degree rule and level accurate to 2°. It is assumed that the direction of No. 4 Deep is N 4° E.
- ii. Positive dip is upward from horizontal.

Table 2 Summary of Results of Biaxial Tests

Drill Hole	Rock Type	Biaxial Test No.	Depth of Sample from Hole Collar (m)	Deformation Modulus (GPa)		
				Individual Diameters		Average
LC4S-1	Siltstone	U1-1B	12.92	U ₁	19.07	19.31
				U ₂	20.63	
				U ₃	18.37	
LC4S-1	Siltstone	U1-3B	13.98	U ₁	38.75	37.48
				U ₂	30.80	
				U ₃	45.96	
LC4S-3	Sandstone	U3-3B	13.13	U ₁	8.50	10.38
				U ₂	11.34	
				U ₃	12.00	
LC4S-4	Siltstone	U4-1B	13.13	U ₁	26.12	28.30
				U ₂	38.52	
				U ₃	23.94	
LC4S-4	Siltstone	U4-2B	13.59	U ₁	26.30	31.74
				U ₂	45.74	
				U ₃	28.88	

Table 3 Magnitudes and Directions of Secondary Principal Stresses

Drill Hole	Test No.	Diametral Displacement of Pilot Hole (μ inch)			Secondary Principal Stresses (MPa)		Orientation of P from Direction of U_1 ($^\circ$)	Elastic Constants for the Evaluation of Stresses	
		U_1	U_2	U_3	Maximum P	Minimum Q		E (GPa)	ν
LC4S-1	U1-1	2786	2102	1600	16.9	12.2	57.5	19.31	0.2
	U1-2	2372	1392	1093	26.2	16.1	51.5	37.48*	0.2
	U1-3	2356	1476	1188	26.4	17.3	51.8	37.48	0.2
LC4S-3	U3-1	93	819	2797	20.1	4.2	112.5	28.30*	0.2
	U3-2	1356	3106	1923	29.2	17.8	69.3	31.74*	0.2
	U3-3	5271	7326	4836	23.7	18.2	55.3	10.38	0.2
LC4S-4	U4-1	1250	1865	1760	17.9	14.1	85.4	28.30	0.2
	U4-2	1398	1903	2189	22.8	18.7	100.6	31.74	0.2

Notes:

1. Diametral displacements are presented in μ inches using the following calibration factors:
 Button No. 1 = 0.918 (μ inch for unit $\mu\epsilon$)
 Button No. 2 = 0.934
 Button No. 3 = 0.958
2. In each test, button set No. 1 was oriented in the vertical plane through the axis of the drillhole.
3. P and Q are respectively the maximum and minimum stresses (secondary principal stresses) measured on the plane perpendicular to the axis of the drillhole.
4. The orientation of P is measured counterclockwise from the U_1 direction.
5. E values are determined from biaxial tests (see Table 2) unless marked * where E is assumed; ν is assumed.
6. The orientations of the drill holes are shown in Table 1.

Table 4 Stress Tensors Calculated by Least Squares Solution

Input Parameters

Drill Hole	Drill Hole Orientation		Test No.	Diametral Displacement of Pilot Hole (μ inch)			Elastic Constants	
	Azimuth (α)	Dip (ψ)		U_1 ($\theta=90^\circ$)	U_2 ($\theta=150^\circ$)	U_3 ($\theta=30^\circ$)	E (GPa)	ν
LC4S-1	124°	30°	U1-1	2786	2102	1600	19.31	0.2
LC4S-1	124°	30°	U1-2	2372	1392	1093	37.48*	0.2
LC4S-1	124°	30°	U1-3	2356	1476	1188	37.48	0.2
LC4S-3	79°	20°	U3-2	1356	3106	1923	31.74*	0.2
LC4S-4	79°	4°	U4-1	1250	1865	1760	28.30	0.2
LC4S-4	79°	4°	U4-2	1398	1903	2189	31.74	0.2

Notes:

1. θ is the angle between the h_1 axis of the drill hole and the diameter across which the deformation was measured (see Figure D.1 in Appendix D for notation of the coordinate system for the drill hole).
2. Only data from successful overcoring tests in siltstone are used for this least squares solution.
3. E values are determined from biaxial tests where recovered samples were long enough to test. For those values marked * E and ν are assumed.

Table 5 Stress Tensors Calculated by Least Squares Solution

Results of Least Squares Solution

(i) Average Stress Tensor

$\sigma_x (\sigma_{E-W})$	= 33.19 MPa	τ_{xy}	= 9.02 MPa
$\sigma_y (\sigma_{N-S})$	= 21.21 MPa	τ_{yz}	= 0.33 MPa
σ_z	= 20.15 MPa	τ_{zx}	= 3.33 MPa

(ii) Statistical Interpretation

Coefficient of Correlation	R	= 0.96
Standard Deviation of Regression Line	S	= 461 μ inches
Standard Deviations of the Stress Components	s (σ_x)	= 19.07 MPa
	s (σ_y)	= 1.65 MPa
	s (σ_z)	= 3.85 MPa
	s (τ_{xy})	= 4.27 MPa
	s (τ_{yz})	= 1.06 MPa
	s (τ_{zx})	= 7.21 MPa

(iii) Magnitudes and Directions of Principal Stresses

<u>Principal Stresses</u>	<u>Azimuth</u>	<u>Dip</u>
σ_1 = 38.45 MPa	297°	9°
σ_2 = 20.55 MPa	31°	24°
σ_3 = 15.55 MPa	9°	-65°

Table 6 Stresses Measured at Different Mines in the Sydney Coalfield

Mine Site	Depth of Test Site (m)	Method of Stress Measurement	Principal Stresses ⁽²⁾ (MPa) (Azimuth/Dip) (°)			Stress Components ⁽³⁾ (MPa)			Overburden Stress (MPa)
			σ_1	σ_2	σ_3	σ_{E-W}	σ_{N-S}	σ_v	
Donkin	165 (12)	overcoring	-	-	-	9.04	7.93	4.90	4.2
No. 26 Colliery	852 (90)	overcoring	26.3 (278/64)	24.05 (9/13)	23.2 (270/-25)	23.31	24.98	25.27	21.7
Prince	222 (20)	overcoring	11.8 (263/14)	9.54 (352.2/5)	5.1 (64/-75)	10.76	9.51	6.00	5.5
		hydrofracturing	17.8 - 25.4 (274/0)	12.8 - 14.1 (6/0)	5.4 - 5.9 (-)	-	-	-	
Lingan (1986)	593 (70)	overcoring	33.84 (88/4)	14.49 (4/-55)	12.21 (355/35)	33.73	13.76	13.05	14.3
		hydrofracturing	-	-	7.8 - 15.4 (-)	-	-	-	
Lingan (1991)	820 (90)	overcoring	38.45 (297/9)	20.55 (31/24)	15.55 (9/-65)	33.19	21.21	20.15	20.8
Phalen	425 (50)	overcoring	21.66 (319/19)	16.22 (69/44)	11.28 (33/-40)	17.44	16.98	14.73	10.7

Notes:

1. Depth below sea level; Figure in () indicates approximate depth of water.
2. σ_1 , σ_2 , σ_3 : Major, intermediate and minor principal stresses.
3. σ_{E-W} , σ_{N-S} , σ_v : Stress components in E-W, N-S and vertical directions.

Table 7 Comparison of In situ Stresses for Langan Colliery and No. 26 Colliery

Mine Site	Principal Stresses ⁽¹⁾ (MPa) (Azimuth/Dip) (°)			Horizontal Stresses ⁽²⁾ (MPa) (Azimuth) (°)		Horizontal Stress Ratio	Stress Components ⁽³⁾ (MPa)		
	σ_1	σ_2	σ_3	σ_{max}	σ_{min}		σ_{E-W}	σ_{N-S}	σ_v
No. 26 Colliery	26.3 (278/64)	24.05 (9/13)	23.2 (270/-25)	25.0 (179)	23.3 (269)	1.07	23.31	24.98	25.27
Langan (1986)	33.84 (88/4)	14.49 (4/-55)	12.21 (355/35)	33.7 (91)	13.8 (181)	2.45	33.73	13.76	13.05
Langan (1991)	38.45 (297/9)	20.55 (31/24)	15.55 (9/-65)	38.0 (118)	16.4 (208)	2.32	33.19	21.21	20.15

Notes:

1. $\sigma_1, \sigma_2, \sigma_3$: Major, intermediate and minor principal stresses.
2. $\sigma_{max}, \sigma_{min}$: Maximum and minimum horizontal stresses calculated from stress components σ_{E-W} and σ_{N-S} using equations given by Hoek and Brown⁴ (1980).
3. $\sigma_{E-W}, \sigma_{N-S}, \sigma_v$: Stress components in E-W, N-S and vertical directions.

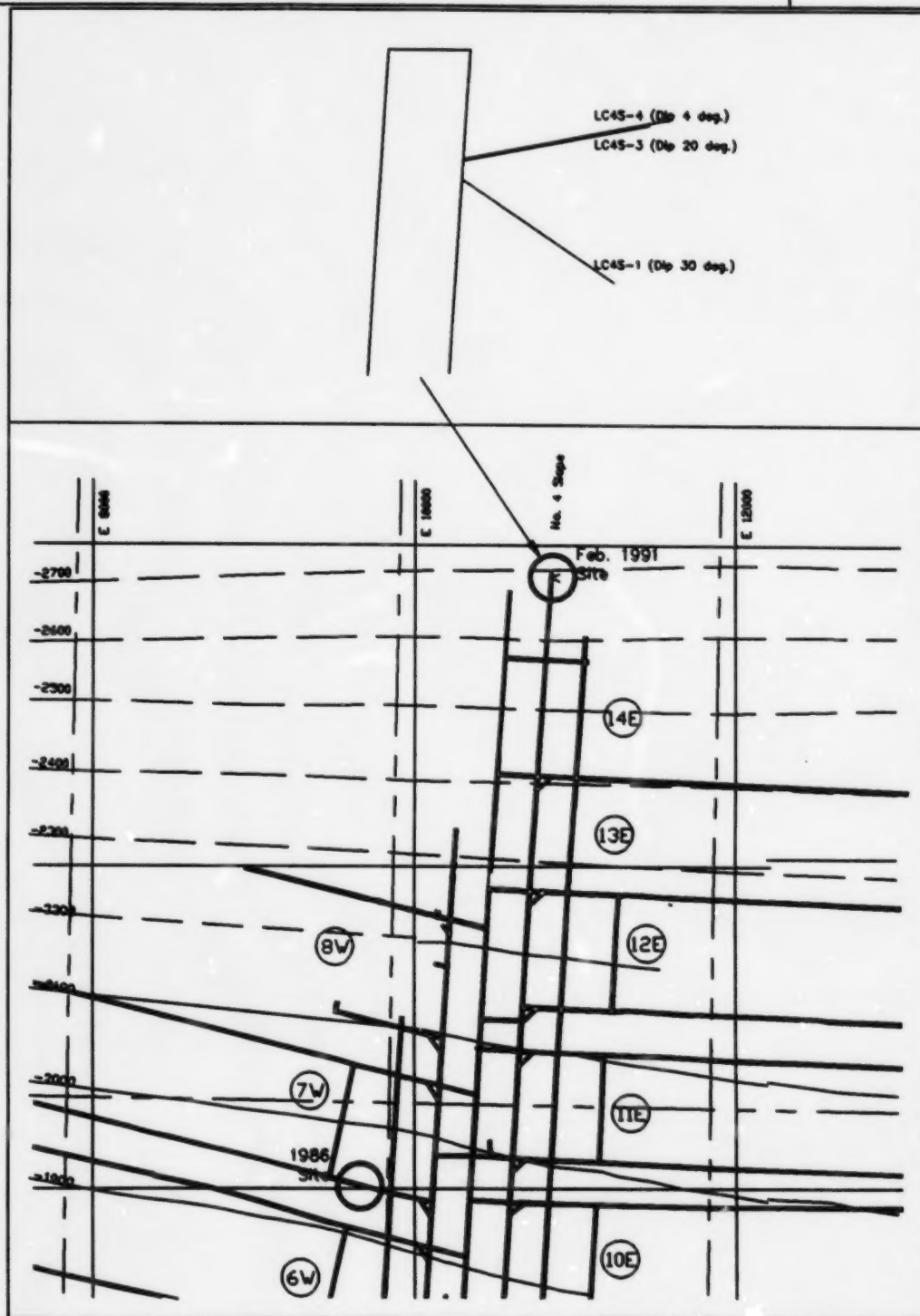
SITE LOCATION PLAN

FIGURE 1



LOCATION OF STRESS MEASUREMENTS LINGAN COLLIERY

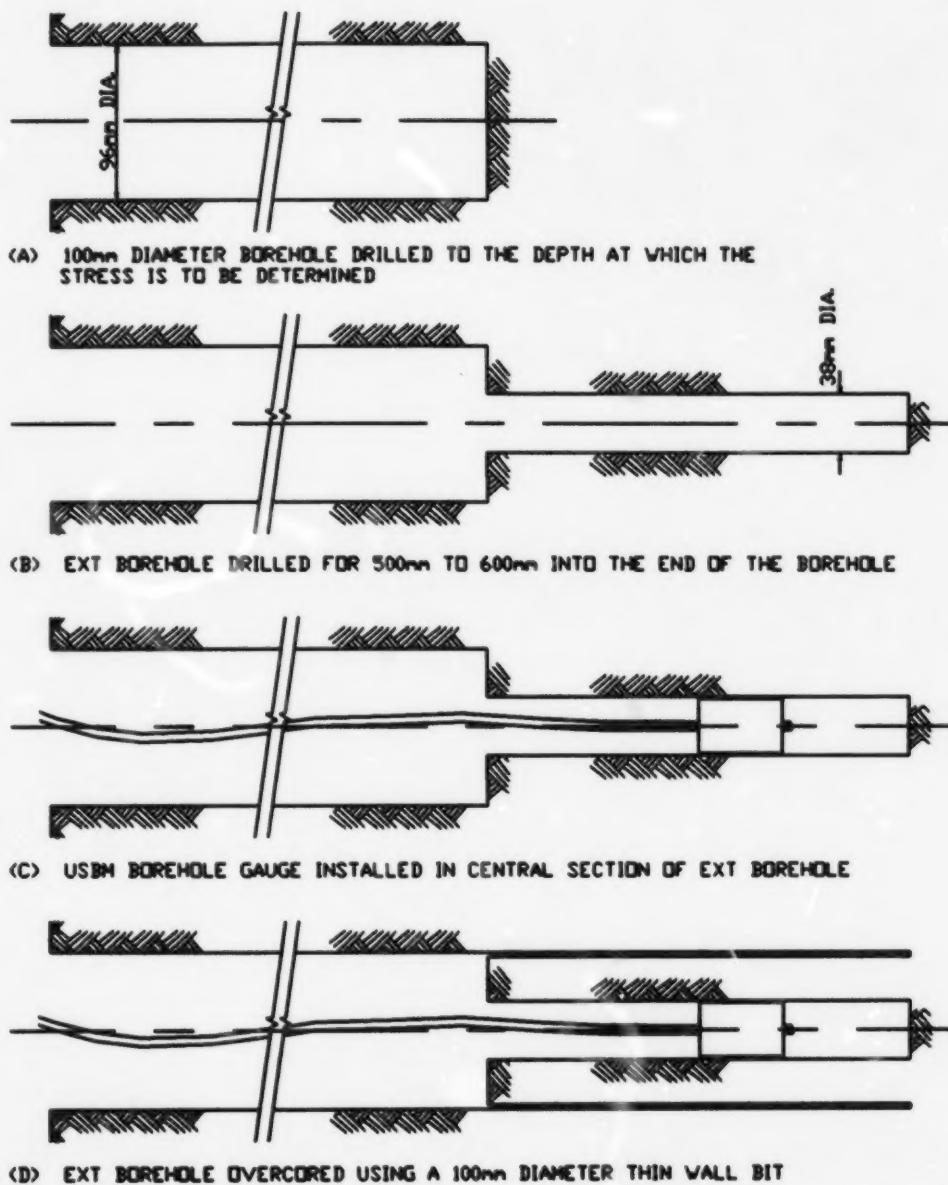
FIGURE 2



Not to Scale

STRESS MEASUREMENT BY OVERCORING METHOD

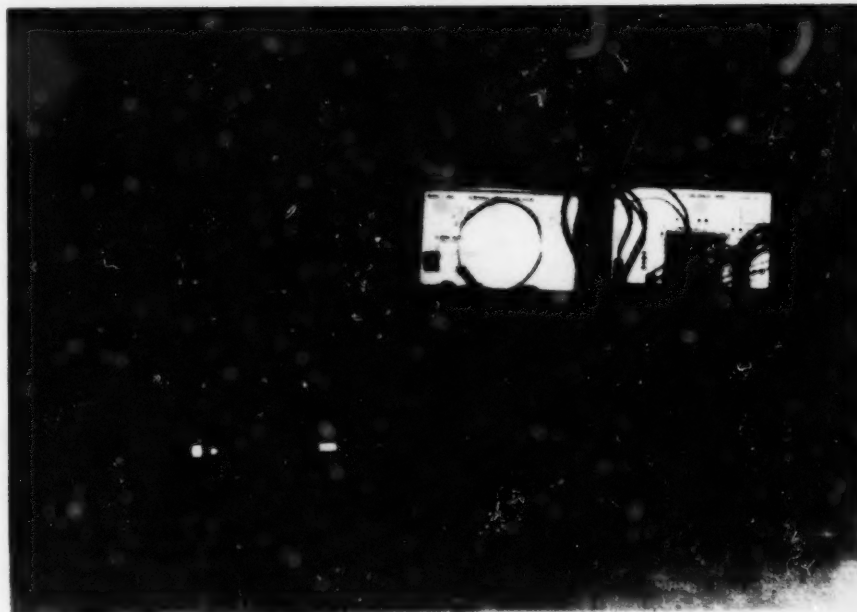
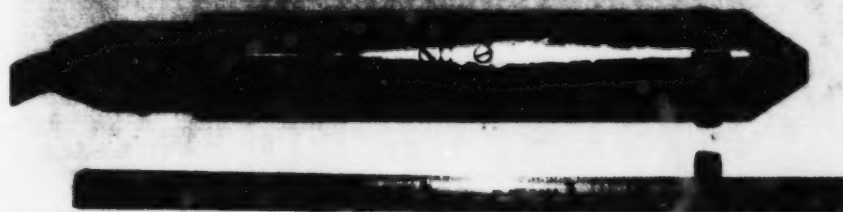
FIGURE 3



NOT TO SCALE

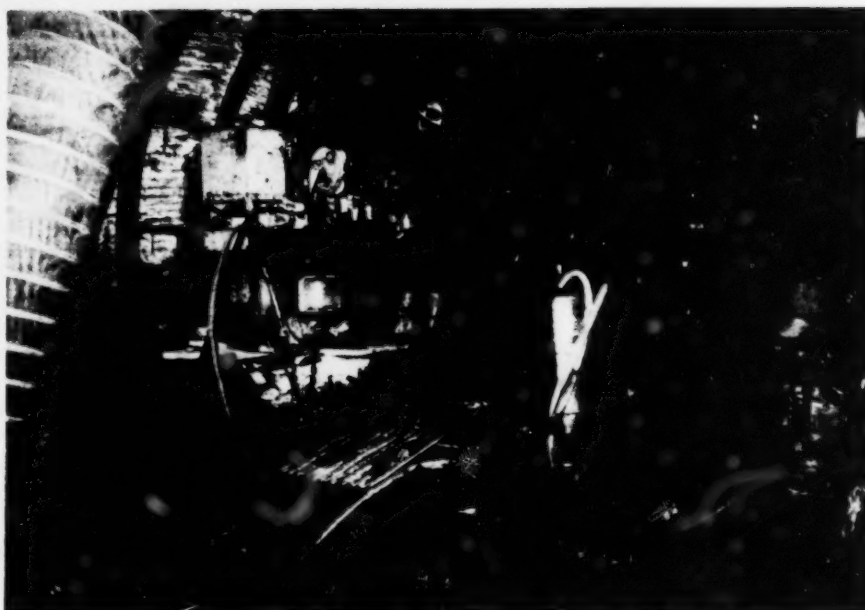
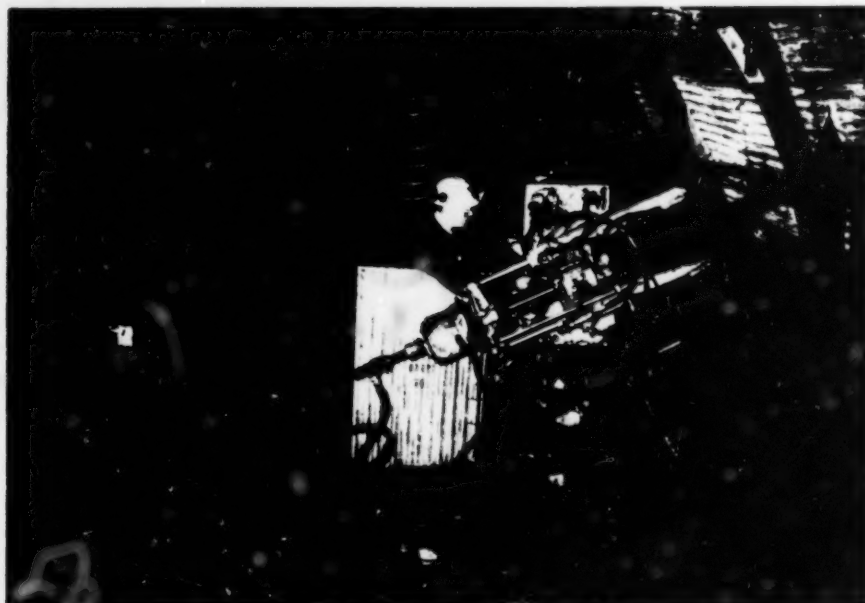
**USBM DEFORMATION GAUGE
AND BIAXIAL TEST EQUIPMENT**

FIGURE 4



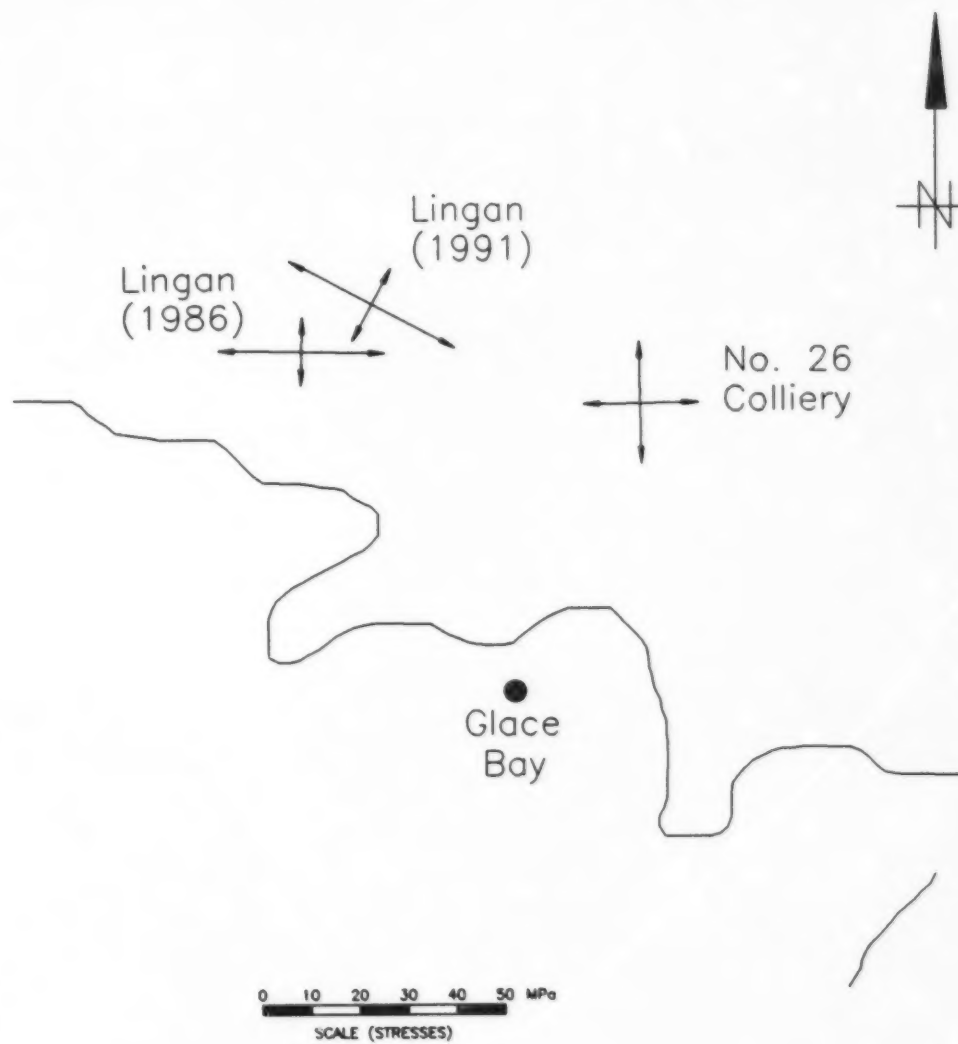
**GENERAL ARRANGEMENT OF DRILLING EQUIPMENT
IN No. 4 DEEP**

FIGURE 5



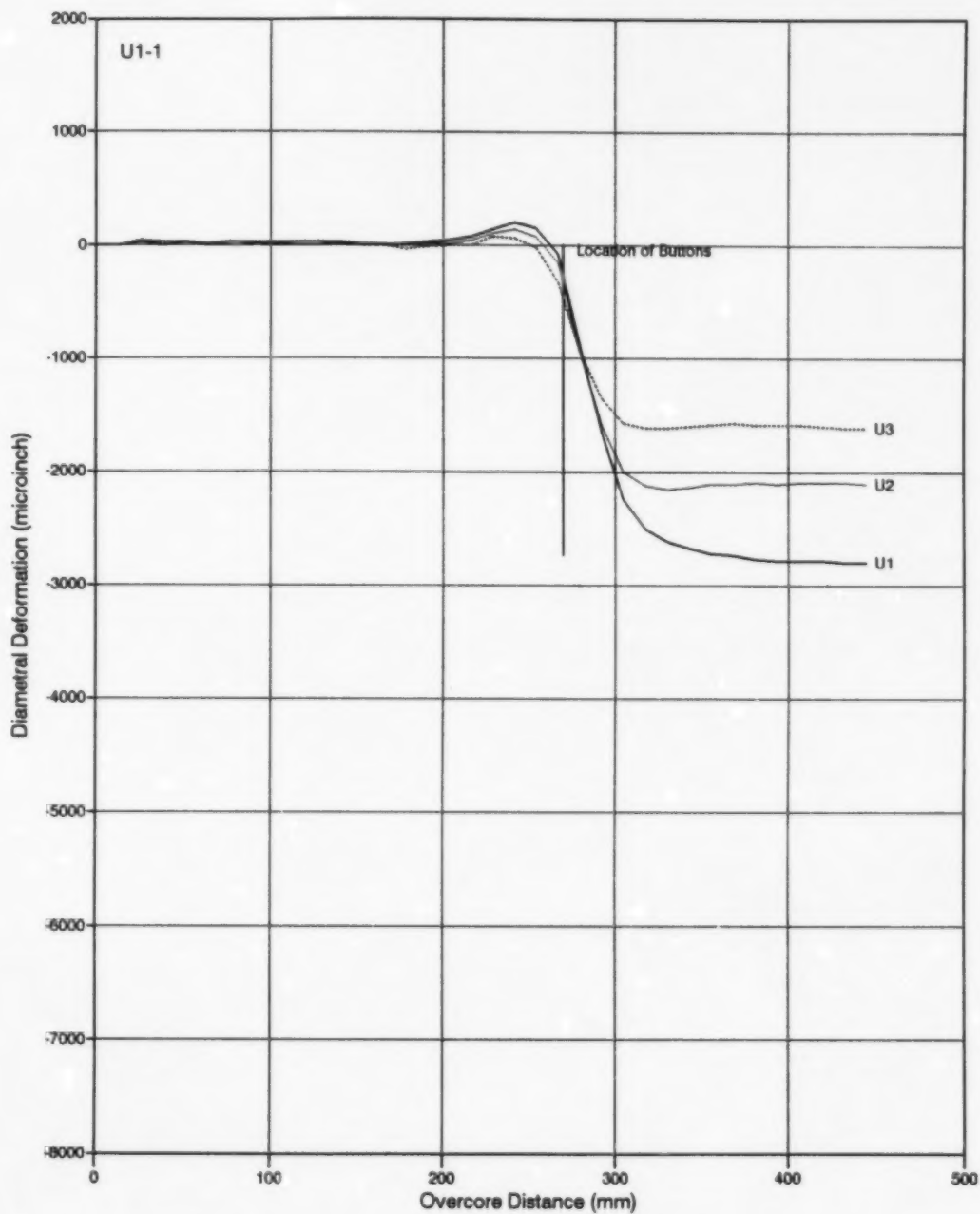
GRAPHICAL PRESENTATION OF HORIZONTAL STRESS VECTORS

FIGURE 6



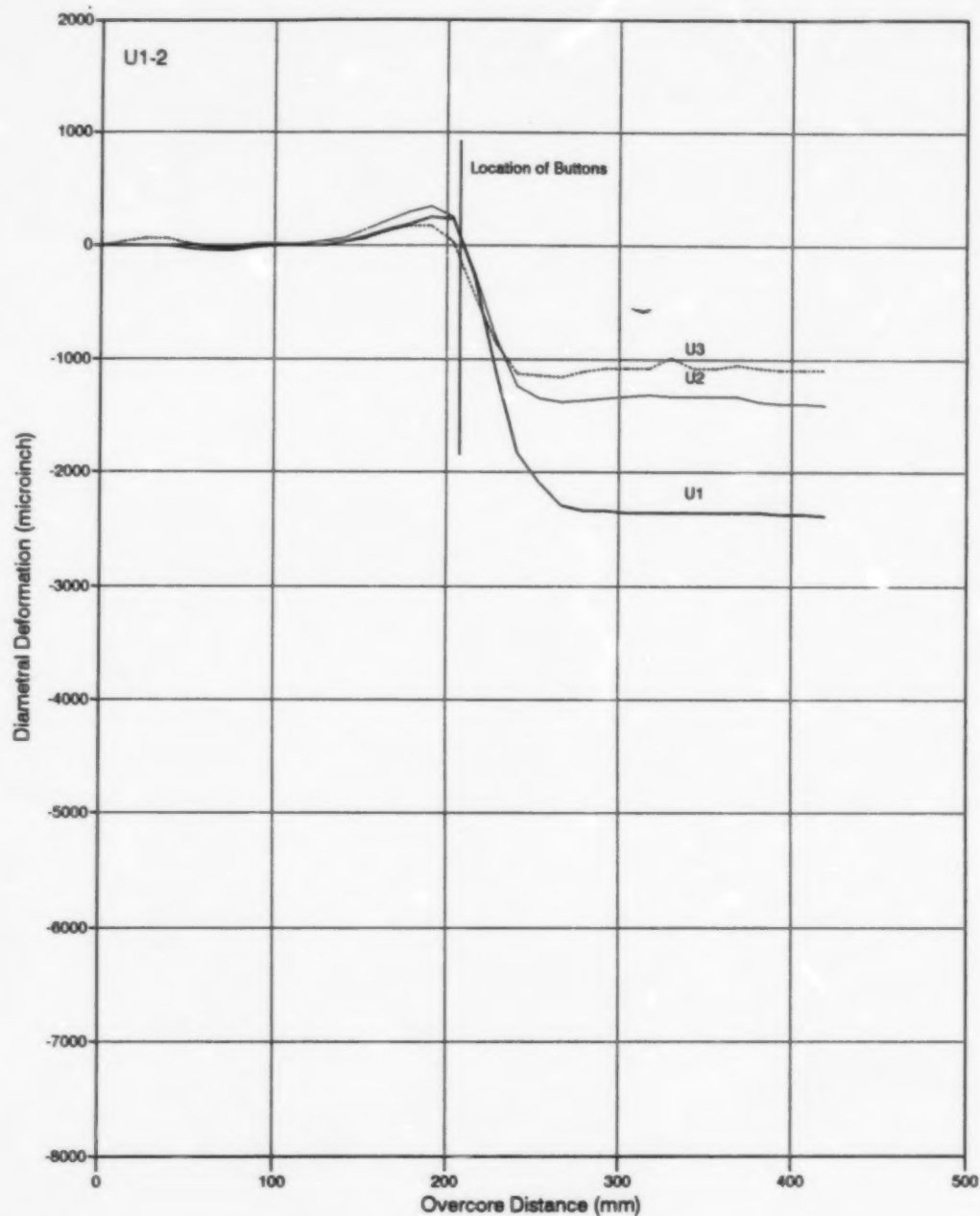
APPENDIX A

RESULTS OF OVERCORING TESTS



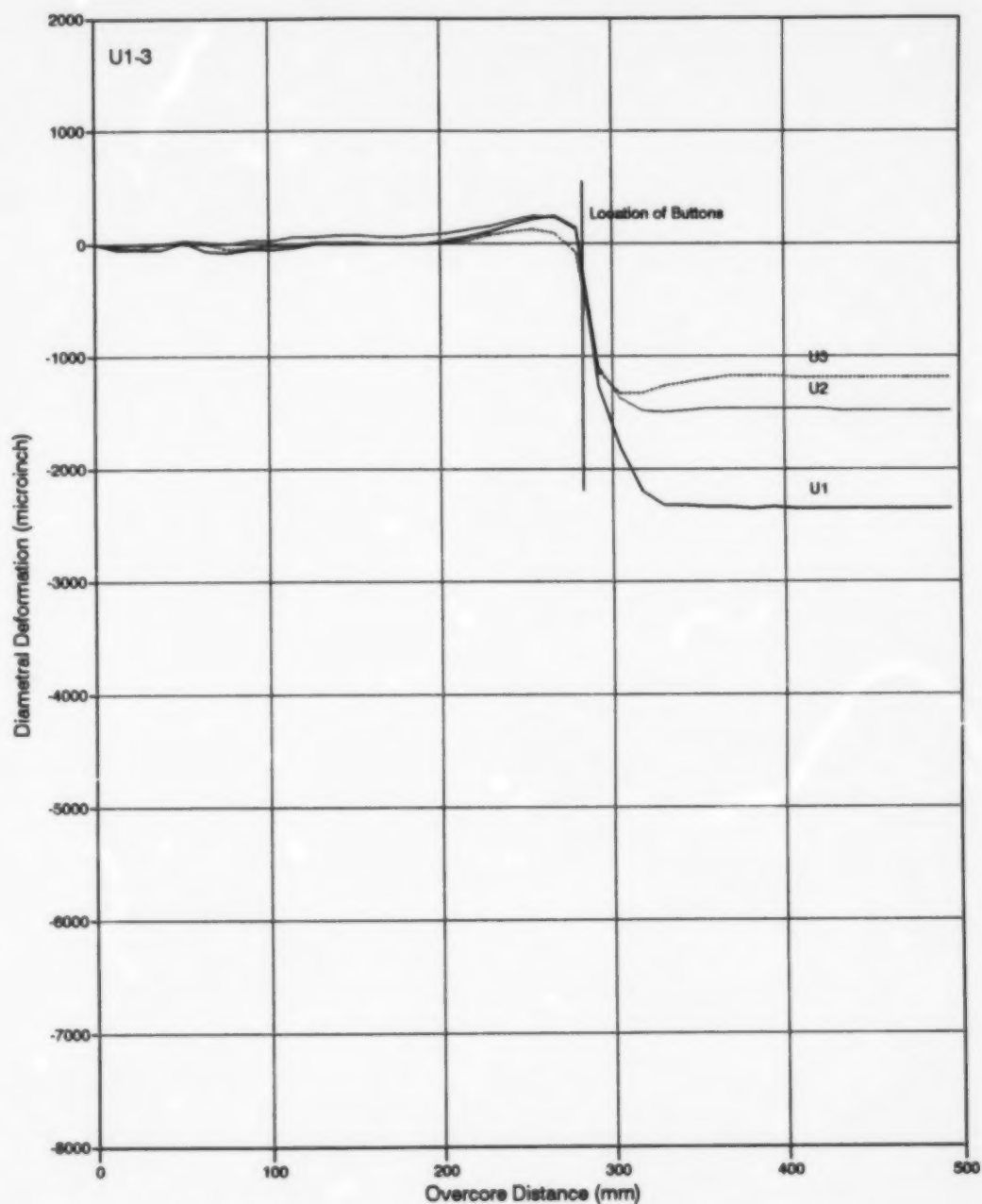
USBM TEST No. U1-2
HOLE No. LC4S-1 Depth 13.55 m

FIGURE A.2



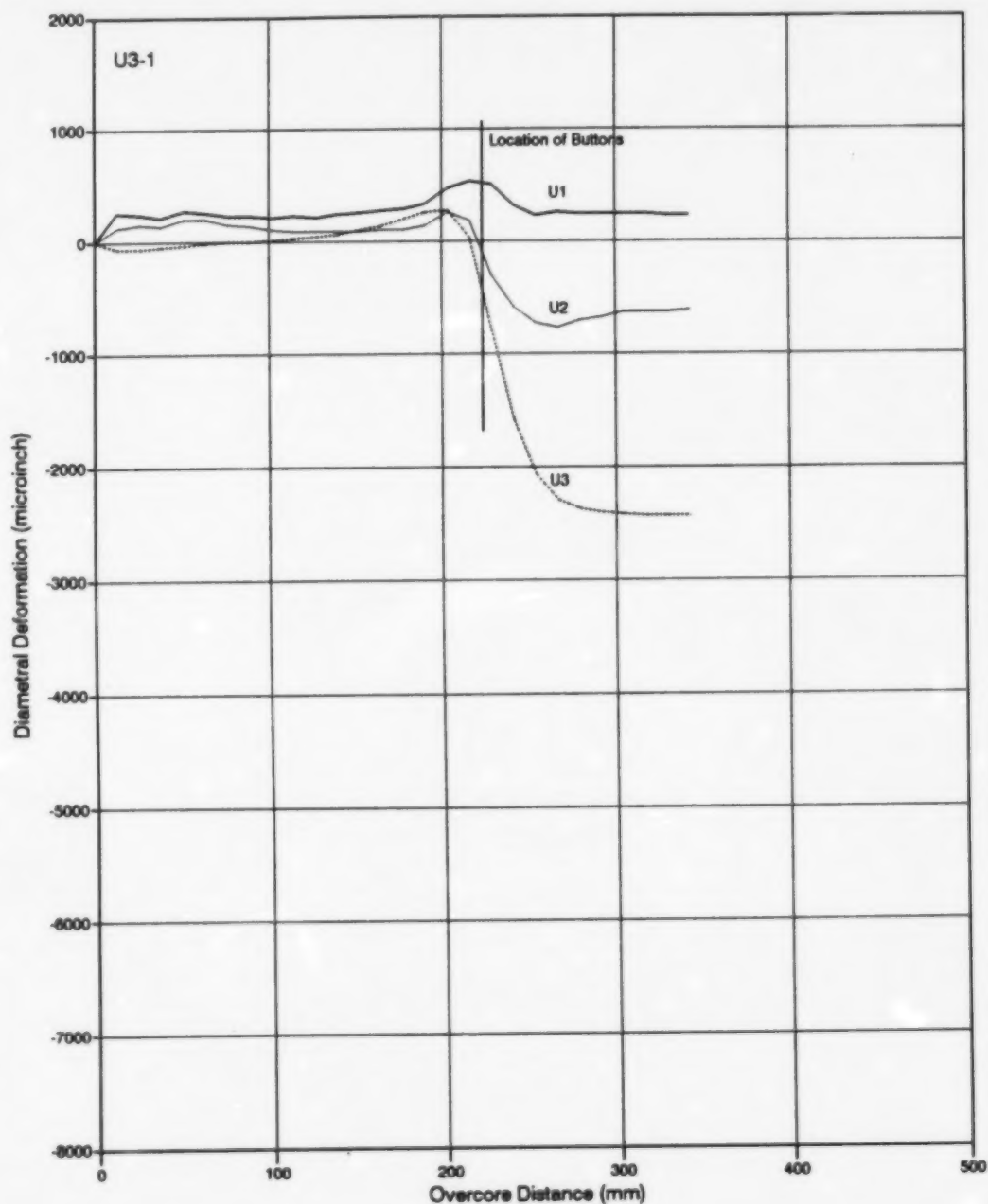
USBM TEST No. U1-3
HOLE No. LC4S-1 Depth 13.98 m

FIGURE A.3



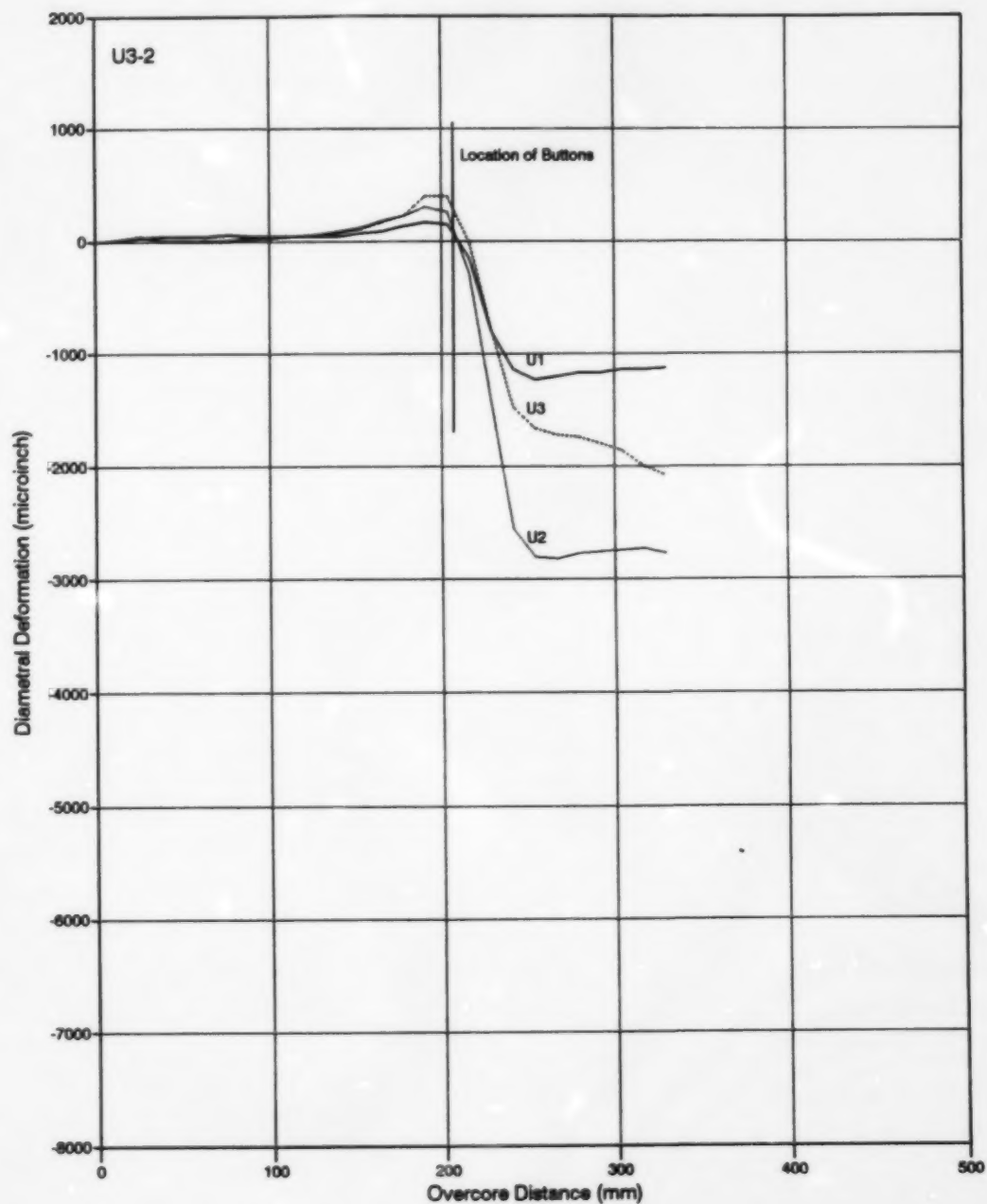
USBM TEST No. U3-1
HOLE No. LC4S-3 Depth 12.50 m

FIGURE A.4



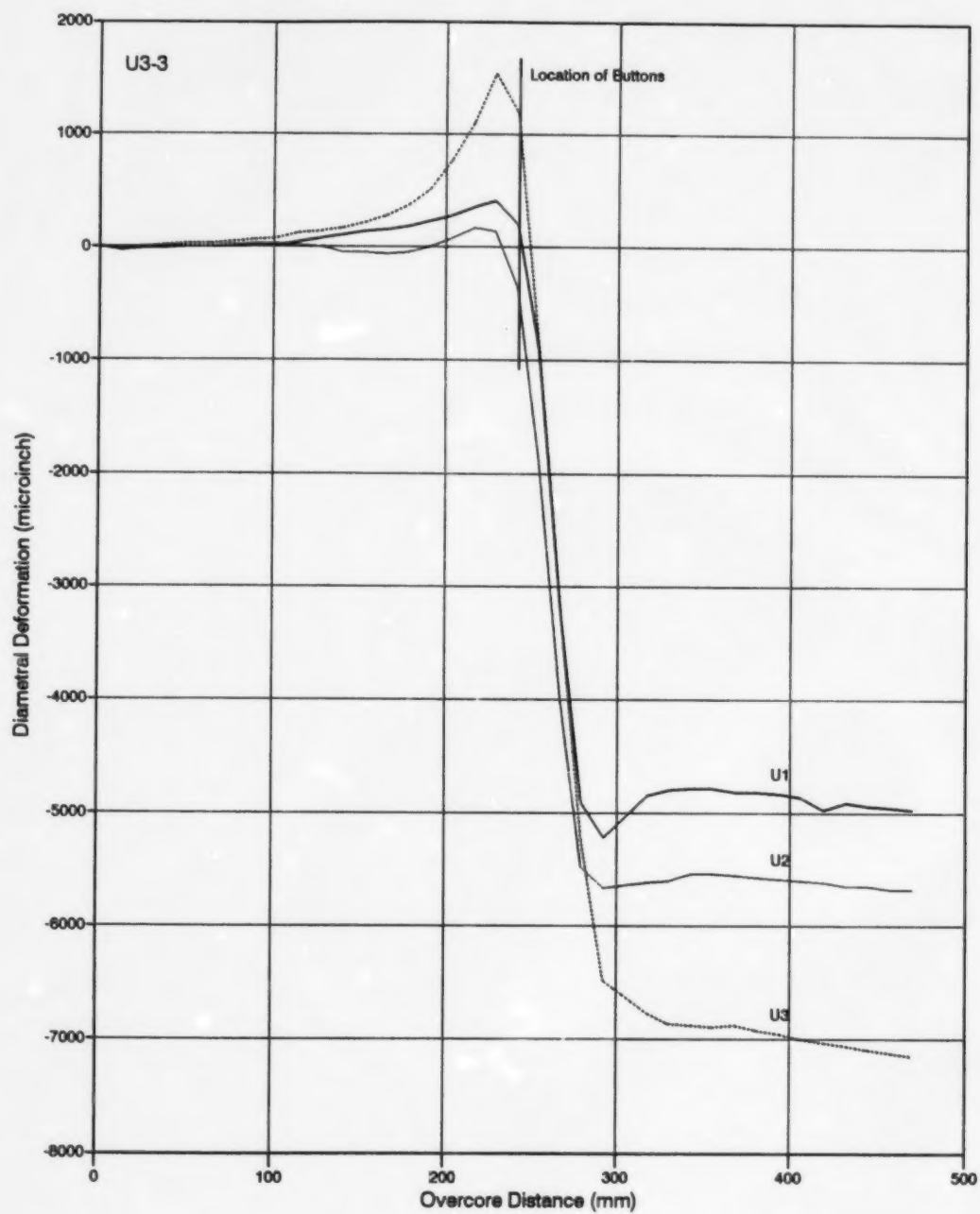
USBM TEST No. U3-2
HOLE No. LC4S-3 Depth 12.78 m

FIGURE A.5



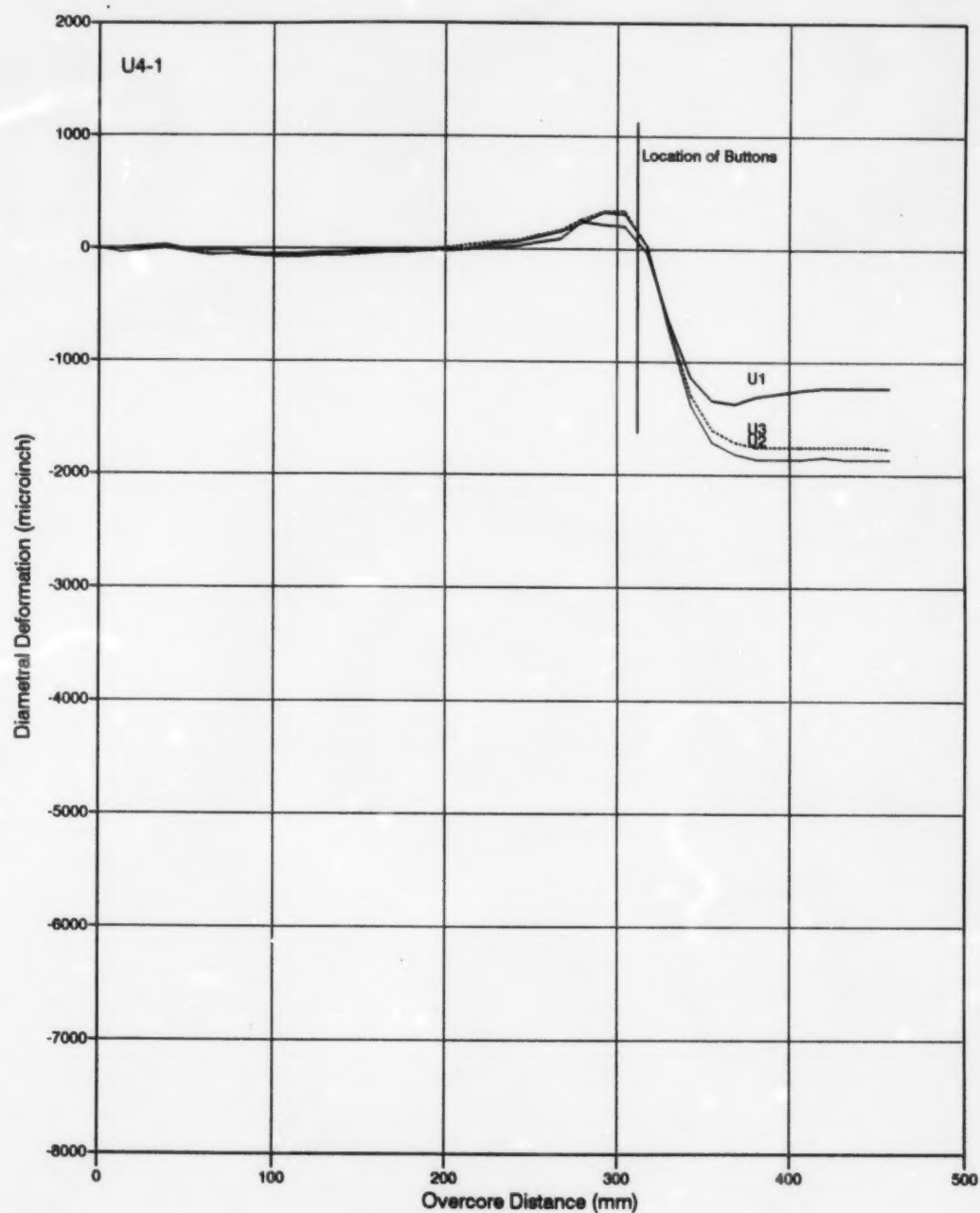
USBM TEST No. U3-3
HOLE No. LC4S-3 Depth 13.13 m

FIGURE A.6



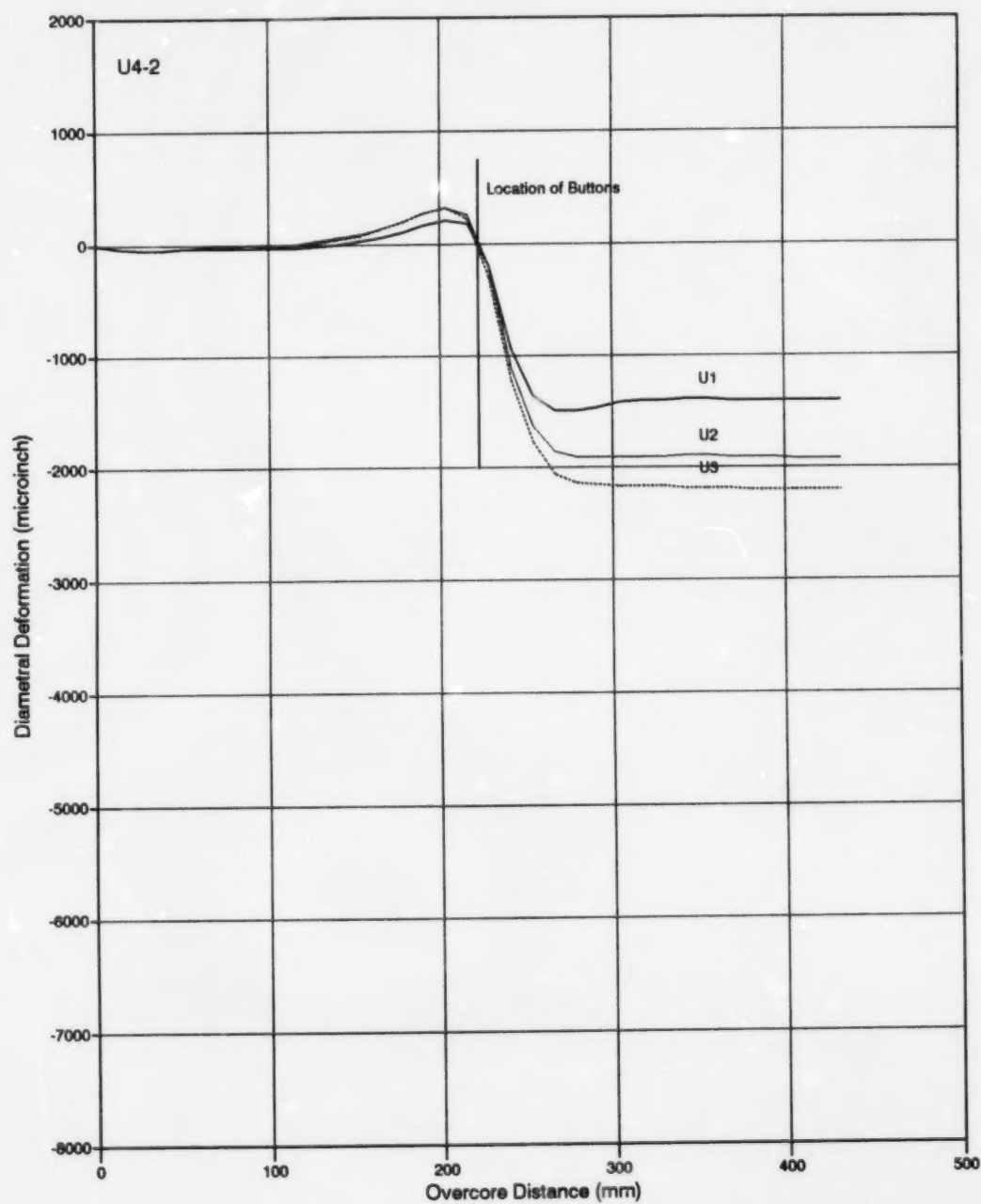
USBM TEST No. U4-1
HOLE No. LC4S-4 Depth 13.13 m

FIGURE A.7



USBM TEST No. U4-2
HOLE No. LC4S-4 Depth 13.59 m

FIGURE A.8

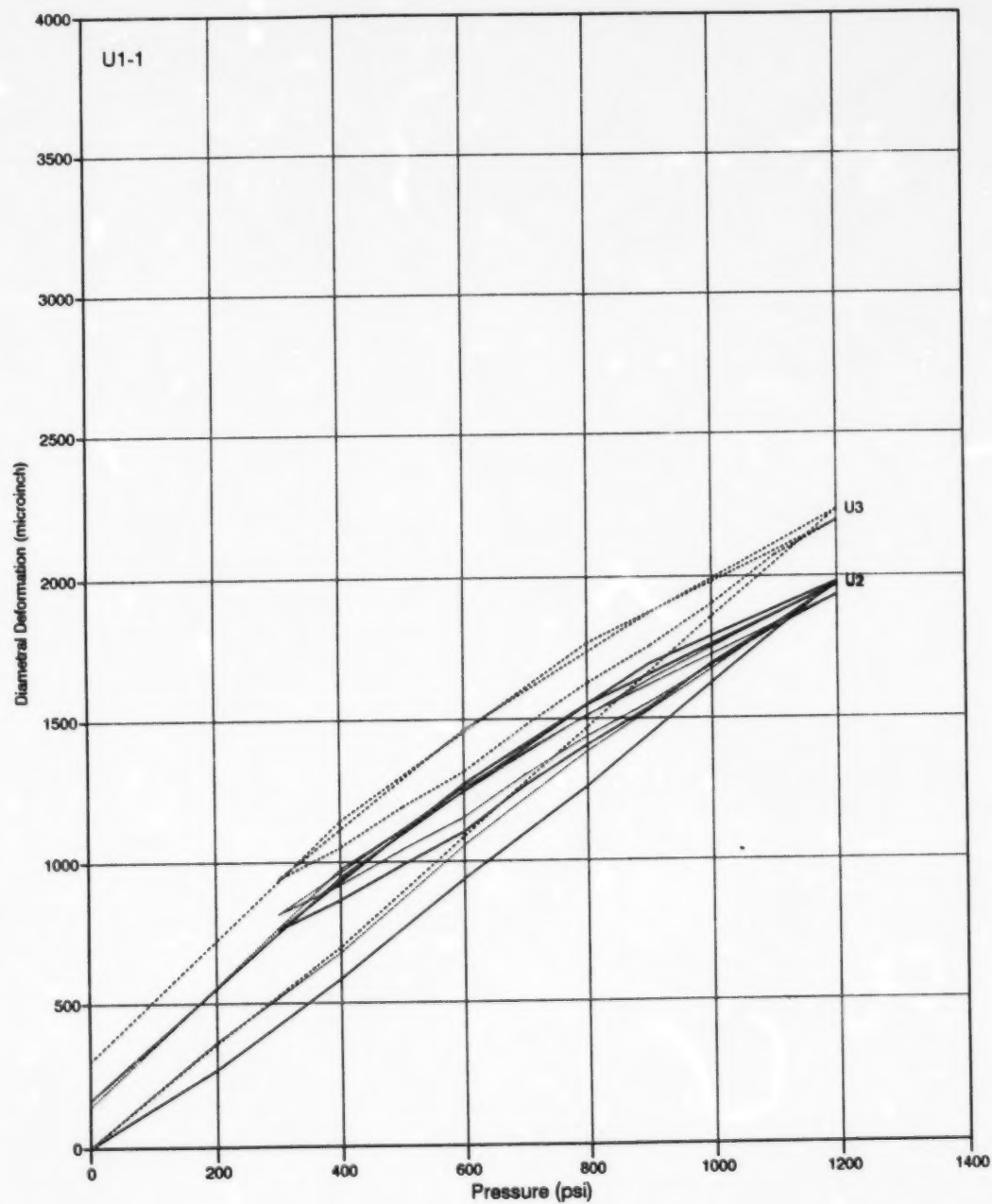


APPENDIX B

RESULTS OF BIAXIAL TESTS

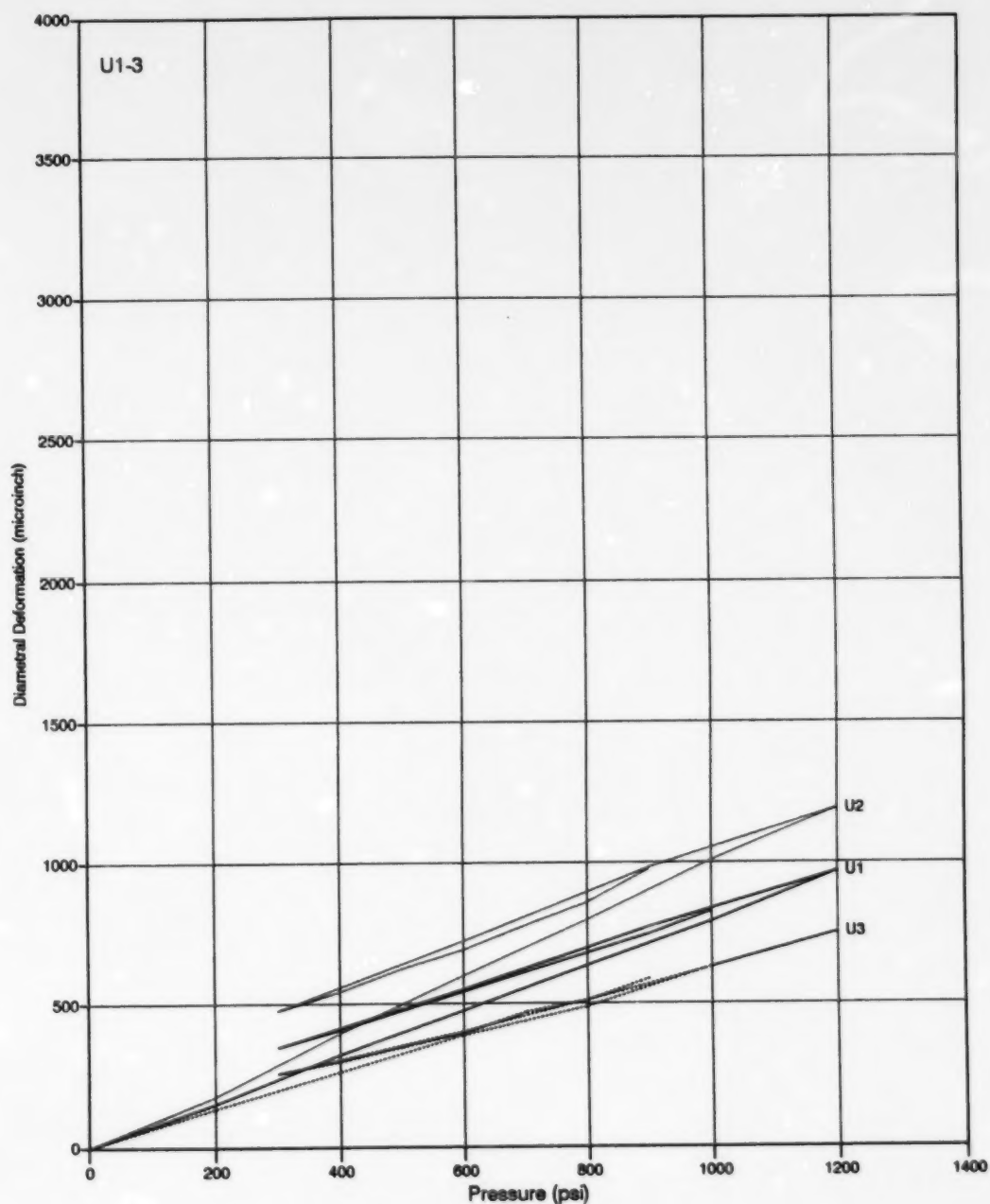
BIAXIAL TEST No. U1-1B
HOLE No. LC4S-1 Depth 12.92 m

FIGURE B.1



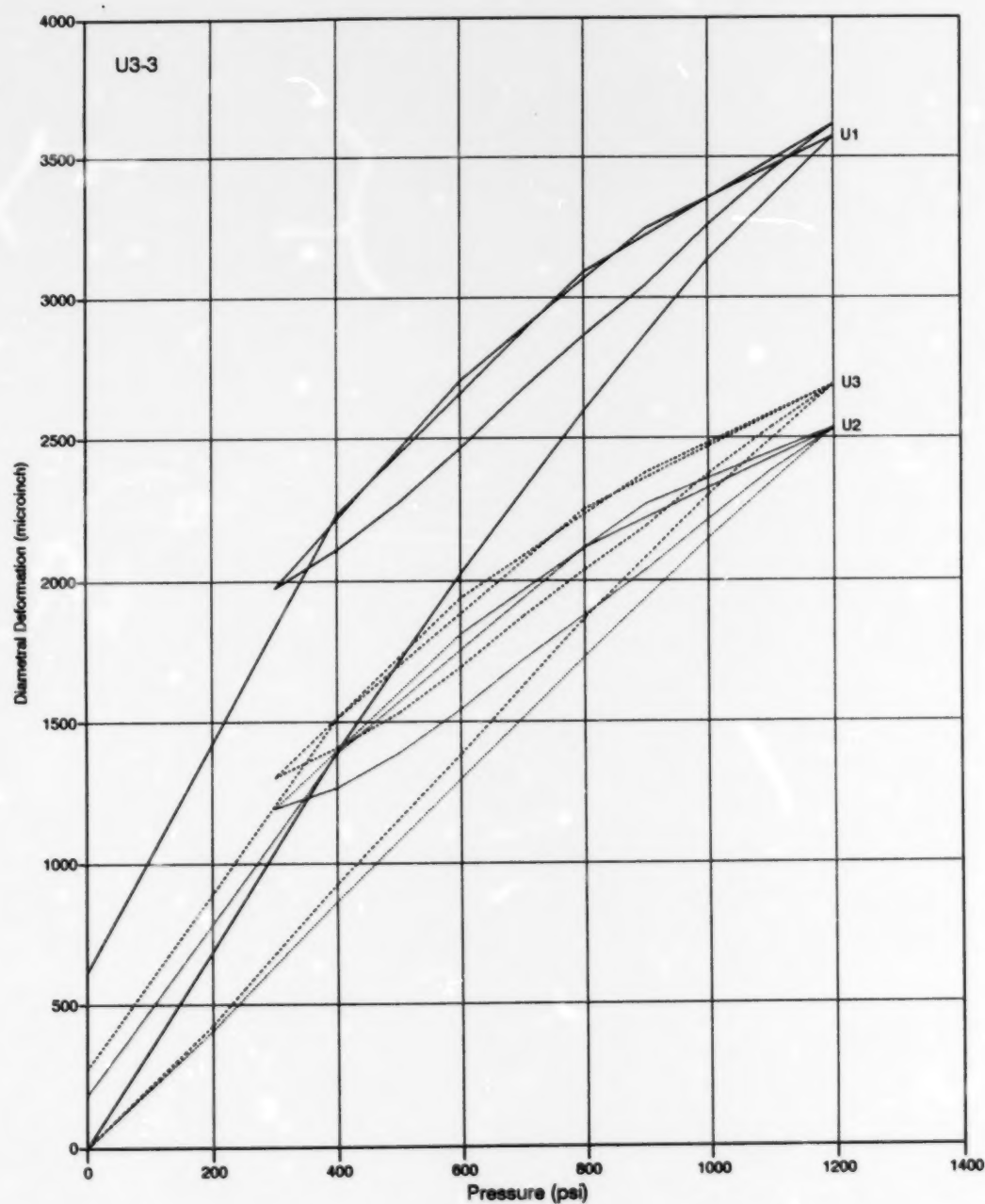
BIAXIAL TEST No. U1-3B
HOLE No. LC4S-1 Depth 13.98 m

FIGURE B.2



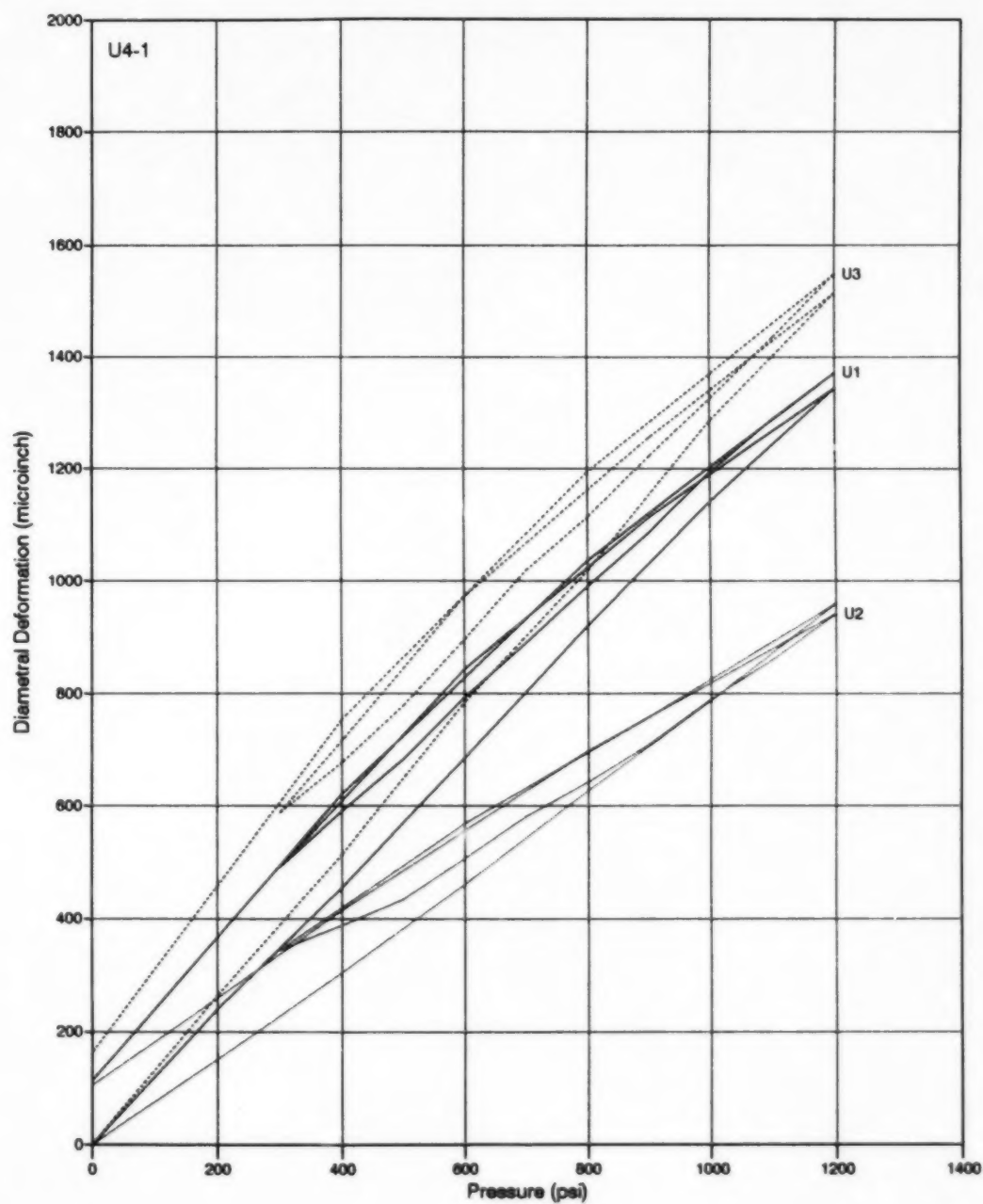
BIAXIAL TEST No. U3-3B
HOLE No. LC4S-3 Depth 13.13 m

FIGURE B.3



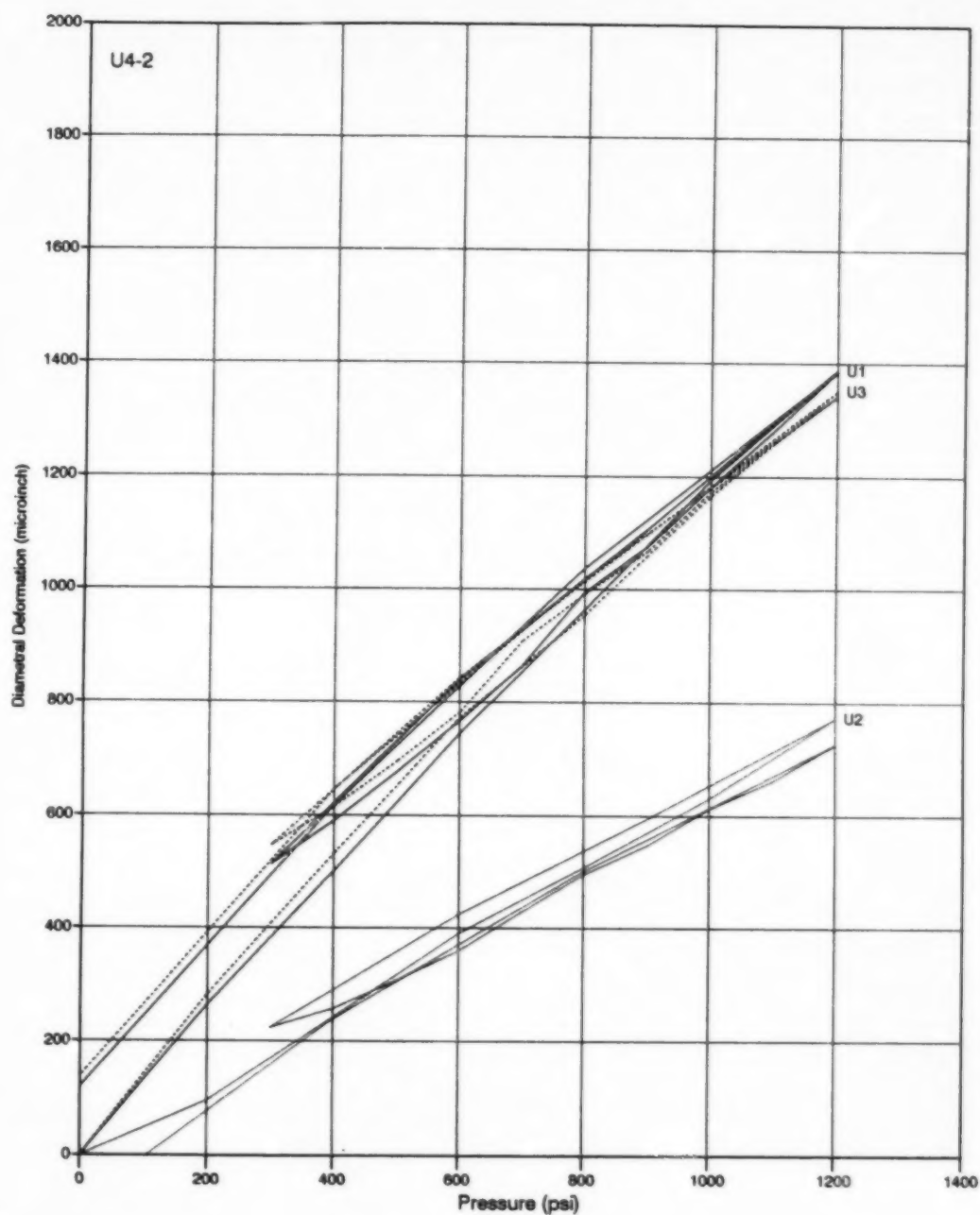
BIAXIAL TEST No. U4-1B
HOLE No. LC4S-4 Depth 13.13 m

FIGURE B.4



BIAXIAL TEST No. U4-2B
HOLE No. LC4S-4 Depth 13.59 m

FIGURE B.5



APPENDIX C

SPECIALIZED DRILLING EQUIPMENT
FOR OVERCORING

The equipment described in this Appendix pertains to overcoring using a 96 mm diameter hole and a 38 mm diameter pilot hole. The overcoring equipment was designed to adapt to the commercially available HQ wireline drilling equipment and can be used either in horizontal or vertical down holes. The components of the drilling equipment are as follows:

- (a) Underground drill rig capable of driving HQ equipment such as the Longyear 38 or equivalent.
- (b) Water pump complete with pressure gauge.
- (c) Special water swivel.
- (d) Standard HQ wireline drilling equipment with HQ driving rods.
- (e) Modified inner tube assembly for the HQ system which carries the starter barrel for the E hole and the 0.6 m to 1 m long double tube E core barrel. This modified assembly latches in place of the conventional HQ inner tube assembly and is rotated and/or fed with the HQ rods. As the modified inner tube assembly was machined to set concentrically with the HQ outer tube, the E hole drill with this assembly would be concentric with the H hole.

This system of drilling is especially advantageous when carrying out deep measurements in vertical downholes because the wireline system allows substantial saving in the time for breaking up and assembling drill rod for drilling the holes. This system has been used successfully in stress measurements in Nova Scotia and Ontario.

- (f) 96 mm diameter thin-walled overcoring bit adaptable to and driven by HQ rods acting as a continuous string of stabilizers along the drillhole. This eliminates the use of individual stabilizers and hence improves the efficiency.

The above equipment performed satisfactory during the tests.

APPENDIX D

**PROCEDURES FOR EVALUATION OF
IN SITU STRESSES FROM OVERCORING
TEST DATA**

D.1 EVALUATION OF SECONDARY PRINCIPAL STRESSES FROM OVERCORING TEST DATA

Based on the deformations measured across the three diameters, the secondary principal stresses on the plane perpendicular to the axis of the drillhole are given by the following expressions (Obert and Duvall, 1967).

$$P = \frac{E}{6d(1-\nu^2)} \left(U_1 + U_2 + U_3 + \frac{1}{\sqrt{2}} [(U_1 - U_2)^2 + (U_2 - U_3)^2 + (U_3 - U_1)^2]^{1/2} \right) \quad D1$$

$$Q = \frac{E}{6d(1-\nu^2)} \left(U_1 + U_2 + U_3 - \frac{1}{\sqrt{2}} [(U_1 - U_2)^2 + (U_2 - U_3)^2 + (U_3 - U_1)^2]^{1/2} \right) \quad D2$$

where E is the average deformation modulus
 ν is the Poisson's ratio
 d is the diameter of the pilot hole
 and U_1, U_2, U_3 are the measured changes in borehole diameter across three diameters at 60° rotation
 U is positive for an increasing diameter
 P is the maximum secondary principal stress
 Q is the minimum secondary principal stress

The direction of P is given by:

$$\theta = \frac{1}{2} \tan^{-1} \left[\frac{\sqrt{3} (U_2 - U_3)}{2U_1 - U_2 - U_3} \right] \quad D3$$

where θ is the angle to P measured counterclockwise from the direction of the U_1 diameter.

The quadrant of θ may be determined as follows,

if $U_2 > U_3$ and $U_2 + U_3 < 2U_1$
 $U_2 > U_3$ and $U_2 + U_3 > 2U_1$

then θ is between 0° and 45°
 then θ is between 45° and 90°

$$\begin{aligned} U_2 < U_3 \text{ and } U_2 + U_3 > 2U_1 \\ U_2 < U_3 \text{ and } U_2 + U_3 < 2U_1 \end{aligned}$$

then θ is between 90° and 135°
 then θ is between 135° and 180°

The above equations are derived for plane strain conditions with zero axial strain ($\epsilon_z = 0$) along the drillhole. If the effect of axial strain is taken into account, an estimate of the axial stress along the borehole is required. Based on the results obtained from the complete solution of the stress tensor, it was noted that the secondary principal stresses based on non-zero axial strain is only about 7 percent higher than those based on zero axial strain.

The deformation modulus of the rock was evaluated based on the results of the biaxial tests using the following expression and assuming isotropic elasticity.

$$E = \frac{4ab^2P_o}{(b^2 - a^2)U} \quad D4$$

where

a

b

P_o

and U

E

= Deformation modulus

= the inner radius of the overcore

= the outer radius of the overcore

= pressure on the outer surface of the overcore

= Diametral deformation of pilot hole in the overcore